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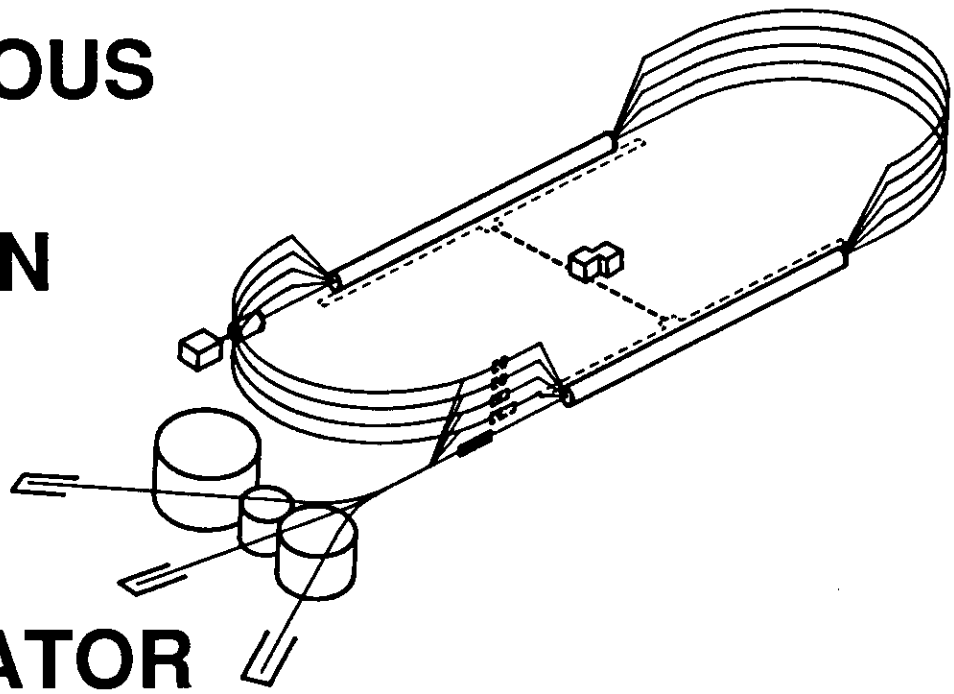

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MICROWAVE ABSORPTION BY LOSSY CERAMIC MATERIALS *

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ABSTRACT

Microwave energy generated by the electron beam in the superconducting cavities of the Continuous Electron Beam Accelerator Facility (CEBAF) is absorbed by special loads fabricated with a novel lossy ceramic material (AlN-glassy carbon) developed especially for this application. Strict environmental constraints (ultra-high vacuum compatibility, operation at 2 K, brazeability, etc.) are imposed on the materials which can be used. Several other ceramics were sintered with AlN and various minority conductive powders to obtain the desired electrical properties according to the "artificial dielectric" model. Dielectric permittivity data and results of low temperature measurements are reported.

INTRODUCTION

Materials capable of absorbing microwaves or, in general, electromagnetic radiation, can rely on several loss mechanisms: the description of the losses is complicated, and the materials used for absorption are often selected based on empirical criteria. It is possible, however, to produce materials in which one loss mechanism dominates over the others, and for which the microwave losses can be controlled over a wide range of temperatures and over a chosen frequency band. The possibility of controlling such properties is particularly useful in a number of accelerator applications.

In many particle accelerators being built or presently being designed (SSC, LEP, high current storage rings etc.) microwave power generated by the charged particle beams (in some cases from below 1 GHz to several hundred GHz and with power ranging from a few watts to several kilowatts per load) must be suppressed and absorbed to prevent beam instabilities. In all these cases materials are required which must be compatible with ultra-high vacuum (less than 10^{-10} torr), and which must be capable of handling large power dissipation (this implies good thermal conductivity and the possibility of brazing them to effectively remove the energy deposited by the microwaves). The materials to be employed cannot contain organic compounds and must withstand large temperature excursions during medium-temperature bakeout of the vacuum structures. Ceramic materials meet all of the conditions imposed by the accelerator environment, but most available materials' dielectric properties are poorly characterized or controlled.

As in other accelerators, absorbers at CEBAF are used to damp higher-order modes (HOM) generated by the electron beam [1]. But at CEBAF the accelerator consists of 338 superconducting cavities and, in addition to the strict environmental constraints common to most accelerators, the microwave absorbers are located in a cryogenic environment at 2 K, the only such arrangement in any accelerator. This additional constraint led to a thorough examination of materials capable of absorbing microwaves and compatible with the severe conditions of the superconducting accelerator. No material was found available which met all of the requirements. Some of the existing materials (e.g., AlN-SiC) which are often used in microwave absorption at room temperature showed temperature dependences related to their semiconducting properties. Most microwave loss mechanisms

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become ineffective at low temperatures because they are related to thermally activated phenomena; an analysis of the possible loss mechanisms reveals that a special class of properly designed materials exists which can provide the necessary interaction with the microwave fields, irrespective of the low temperatures.

LOSS MECHANISMS IN SOLIDS

Electromagnetic losses in solids can be effected by two basic mechanisms: direct photon-phonon conversion in polar dielectric insulators, or through the mediation of electrons from the conduction band in non-insulating materials. The electrons acquire energy from the electromagnetic wave and then deposit it into the lattice in an electron-phonon interaction [2],[3].

The direct photon-phonon conversion phenomenon occurs in insulating dielectrics; the polarization induced in crystal lattices by incoming electromagnetic fields relaxes into normal modes of oscillation, modes which eventually redistribute the electromagnetic energy into thermal phonons. This type of loss mechanism is, in general, not very effective, since it depends on the number of available normal modes of the ions in the lattice, which is a strong function of temperature and of frequency, and it certainly is ineffective at low temperatures, where, for instance, crystalline solids exhibit very low attenuation constants. This process becomes more effective at high temperatures, up to the point where, together with the increasing semiconduction losses, it can lead to thermal runaway phenomena [4],[5]. In a more controlled way, the same loss mechanisms are employed to effect ceramic sintering.

In conducting and semiconducting materials the loss processes involve the presence in the conduction band of electrons which are scattered off ions, impurities, dislocations, grain boundaries etc., exchanging kinetic energy with the lattice. The basic phenomenon is common to many materials, but the exact scattering phenomenon leads to drastically different absorption behaviors.

In semiconducting materials the number of electrons available in the conduction band decreases with temperature, thus leading to substantially different absorption properties as a function of temperature. Moreover, in semiconductors the inherent losses are a strong function of the doping, and the intrinsic resistivity can change by many orders of magnitude by small changes in impurities' composition or concentration and due to vastly different mobilities of electrons and holes.

The loss phenomena based on semiconduction are often difficult to control and might lead to unreliable behavior from sample to sample. This is the case, for instance, of sintered SiC, the resisitivity of which can span over ten orders of magnitude [6].

Both conductors and semiconductors can have loss mechanisms which rely on grain boundary resistance due to hopping conductivity across powder grains: these loss phenomena are often used in microwave systems at room temperature and when small power densities are present. Lossy foams, or even the losses in carbon resistors, are typical examples of these mechanisms which do not depend very strongly on the material's conductivity, but which rely on grain boundary or surface effects: these are mostly thermally excited loss mechanisms and are therefore ineffective at low temperatures.

Metal conductors have electrons in the conduction band at any temperature. These electrons are always available to mediate the photon-electron-phonon interaction, but at microwave frequencies the skin effect prevents absorption on the part of bulk metal materials. However, controlled and effective microwave absorption can be obtained by making use of the metallic behavior of conductive particles suitably dispersed into a dielectric insulating material. This composite is known as an "artificial dielectric".

ARTIFICIAL DIELECTRICS

These materials and their properties have been known for a long time and have been the subject of extensive theoretical and experimental studies [7],[8], [9],[10].

The basic loss mechanism is here given by scattering of electrons within each elementary grain due to the current induced in each grain by the incoming electromagnetic wave. Depending on the size and resistivity of the grains, the losses in each grain can be electric or magnetic, and a particular frequency can be best attenuated [11].

Typically, radiation is best absorbed if the grain diameter is of the order of the skin depth in the grain material. By choosing a proper conducting material in powder form, and by knowing its resistivity, its grain size (or size distribution), its concentration and the dielectric properties of the host material, it is in principle possible to obtain specific combinations of dielectric constant and losses.

The concentration of the conducting particles alters the effective dielectric permittivity of the host material, but it also has a secondary effect on practical materials: if the volume concentration of the conductive phase is larger than 15 percent, then aggregation of particles can take place. In this case, loss mechanisms other than pure ohmic losses within the elementary grains can occur, and these additional losses will be temperature dependent [12].

If the conductor's concentration approaches or exceeds 50 percent, then a metallic behavior will screen the currents from the bulk of the material and absorption will be inhibited (at or above the percolation threshold).

To avoid temperature dependent absorption (at least from 0 K to several hundred degrees C) one must rely solely on the metallic behavior of the minority powders in concentrations below 15 percent by volume and choose powders with the proper sizes and resistivity.

In two limiting cases the resistivity of elementary grains is described by phenomena which are essentially independent of temperature. If the electron mean free path is much smaller than the grain size the conductivity is independent of temperature because the impurity scattering dominates (dirty limit). If the mean free path, conversely, is much larger than the grain size, then scattering at the grain boundary is responsible for the losses, which will be independent of temperature from 0 K to several hundred C. Intermediate cases have in principle a mild temperature dependence, due to the varying skin depth as a function of resistivity (square root law), but this dependence eventually saturates due to the anomalous skin effect. This effect limits the surface resistance variations to a factor of six between room temperature and 0 K. Due to this limited change in microwave losses in elementary grains as a function of temperature, the overall losses in an artificial dielectric will be limited. Because most artificial dielectrics contain a distribution of particle sizes, the changes in losses due to the changing skin depth in a specific grain size will be compensated for by the increased losses in a contiguous grain size [11].

The actual choice of materials that will yield specific electric and magnetic properties is difficult in practice, because of the poor control of powder properties, and becomes even more difficult if the artificial dielectric to be manufactured is in a ceramic form. However, artificial dielectrics present properties which are a much milder function of the constituents' properties than other types of lossy materials, and for this reason ceramic artificial dielectrics can in many cases provide the required loss characteristics.

CERAMIC ARTIFICIAL DIELECTRICS

Lossy ceramic materials have been used in several applications where thermal conductivity, good vacuum properties or high dielectric constant are important. Among these are terminations for traveling wave tubes (TWT's) and lumped resonators in planar microwave circuits. Most of these applications have relied on the semiconducting losses of materials such as SiC, properly sintered by itself or within a ceramic host. In many cases the properties of these materials are not well understood or reproduced, because the very process of sintering can drastically alter the semiconducting properties of the lossy material.

In order to obtain a well-behaved ceramic version of the artificial dielectric materials, the following conditions must be satisfied: a) The conducting material (not semiconducting) cannot melt at the sintering temperature (in the range of 1500 to 2000 C for typical host materials). b) The conducting material cannot react chemically with the host ceramic at the sintering temperature. (Chemical reactions can alter the conducting properties of the original powders beyond the point of prediction of properties.)

The conductivity of the powders can be altered by the high temperature treatment since, for instance, recrystallization at high temperatures tends to lower the resistivity, whereas impurity diffusion tends to increase it. Often unpredictable conductivities can result from these competing mechanisms.

Among the materials which satisfy the above requirements there are just a handful of metals, semimetals, alloys and compounds: W, Mo, Ta, Nb, C and a few other rare metals and their alloys. Most of these materials and compounds can be obtained in a powder form, for instance through plasma spraying techniques [13].

For this work several materials were sintered [14] in a ceramic form, in order to produce specific dielectric properties which would meet required absorption for CEBAF [1]. Among the materials that were tested, we report here on mixtures of ceramics composed of AlN as a matrix, and with conductive powders of Mo, TiC and glassy carbon (an amorphous form of carbon obtained by pyrolysis of phenolic resins) [15].

The relative dielectric constant of AlN is 8.5. The data in Table I show the increase in dielectric constant due to the presence of the conductive powders. The data are consistent with the artificial dielectric model predictions for the given concentrations.

At these frequencies the loss tangent of AlN is negligible compared to the loss tangents of the composite materials. Therefore most of the losses occur within the conductive grains.

Table I. Physical properties of conducting powders

Mat'l	T(melt) [C]	Avg. Grain Size [μm]	Vol. [%]	ϵ_r [@ 2 GHz]	tg δ	ρ [$\mu\Omega$·cm]	δ[@ 2GHz] [μm]
Mo	2617	2.7	12	10	0.02	5.7[16]	2.7
Mo	2617	2.7	15	19.5	0.01	5.7	2.7
Mo	2617	2.7	16	27.5	0.02	5.7	2.7
TiC	3140	15	16	67.5	0.18	170[18]	14.7
TiC	3140	1.3–3	16	18	0.01	170	14.7
TiC	3140	1.3–3	18	23	0.03	170	14.7
TiC	3140	1.3–3	20	32	0.07	170	14.7
C	3550	3–12	15	22	0.16	1k–5k	35–80
C	3550	20–50	15	33	0.22	1k–5k	35–80

The minority conducting phase is always held near or below 15 percent in order to avoid temperature dependent phenomena. In the case of glassy carbon this choice of concentration also provides structural strength even though glassy carbon does not sinter with the dielectric ceramic: larger concentrations would make the structure unstable. Structural integrity considerations not only limit the powder concentration, but also the size of the powders that can be used. Whereas for general artificial dielectrics any powder size can be used, as long as it satisfies the electrical properties criteria, in sintering ceramic structures only a limited range of powder sizes is permissible in order to maintain structural integrity of the composite ceramic. Typical sizes range from less than a micron to several tens of microns. This size limitation has also an impact on the range of grain resistivities which can be chosen to more effectively damp the microwave frequency band.

Table I also gives the expected skin depth in the grains at 2 GHz, a critical frequency to be damped in the CEBAF cavities. For most powders the skin depth and the grain sizes are chosen to be very close at this frequency. The theoretical skin depth of the various materials is calculated at 2 GHz for published values of conductivity of bulk materials [16], except for glassy carbon, the conductivity of which is derived from data of Guillot *et al.* [17].

Measurements of permittivity and loss tangent were performed with an HP85070A dielectric probe kit with an HP8753C network analyzer.

Samples of these materials have been tested for rf properties at room temperature to obtain baseline dielectric data, and then absorbers have been cooled to 2 K to determine the presence or absence of thermally induced absorption phenomena. All of the materials presented here showed no modifications of the dielectric properties with temperature, unlike other samples containing SiC, which show low temperature changes of dielectric properties.

Figure 1. SEM image of an AlN-glassy carbon composite ceramic. The carbon particles are easily identifiable by their spherical shape.

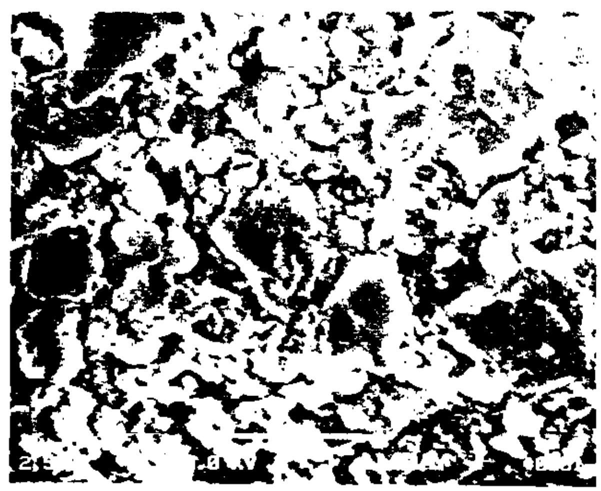

Figure 2. SEM image of the AlN-Mo composite.

For the production of absorbers in the accelerator the AlN-glassy carbon ceramic was chosen, having a reproducibly high loss tangent. The perfectly spherical particles of this material (Figure 1) make a possible theoretical modeling simpler.

The vacuum properties of this fully dense ceramic have been tested and upper limits to its outgassing rates have been set at about 1×10^{-10} (torr liter)/(cm^2 sec).

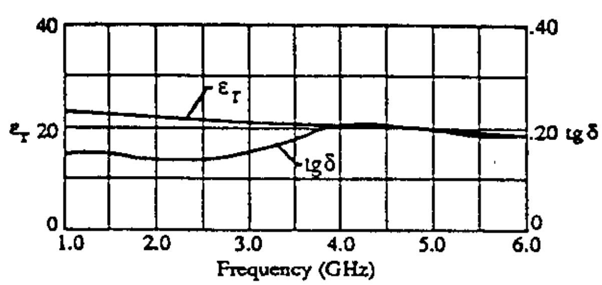

Figure 3. Dielectric permittivity and loss tangent of the AlN-glassy carbon ceramic.

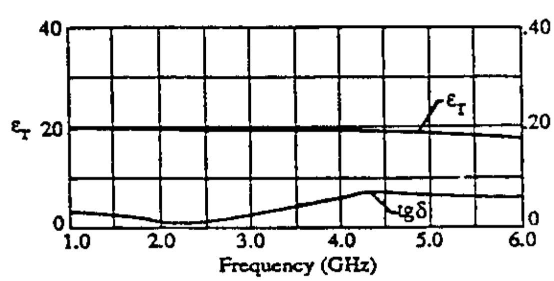

Figure 4. Dielectric permittivity and loss tangent of the AlN-Mo composite.

CONCLUSIONS

Various ceramic materials have been studied and produced for practical applications where microwave absorbers must coexist with very stringent environmental conditions (ultra-high vacuum, low or high temperatures, high power densities etc.). Specific dielectric constants and loss tangents can be achieved and reproduced by using the artificial dielectric model to design the ceramic composition. The additional low temperature studies help in discriminating the basic loss mechanisms which take place in these lossy ceramics. The resulting understanding can benefit both the development of methods to sinter ceramics through microwave absorption and the development of ceramics sintered for microwave absorption applications.

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